

FLOW LOSSES IN FLEXIBLE HOSE

SUMMARY REPORT

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Approved by:



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Introduction:

A contract was awarded Louisiana State University on June 14, 1965, by the Manned Spacecraft Center, Houston, Texas for the purpose of investigating Flow Losses in Flexible Hose. The work was under the direction of Dr. Charles A. Whitehurst of the Department of Mechanical and Aerospace Engineering and Dr. Bernard S. Pressburg of the Chemical Engineering Department. Experimental work was carried out by graduate students from these departments. Other members of the engineering faculty and the Division of Engineering Research contributed knowledge and advice to the completion of the project.

Study Objectives:

The primary objective of this investigation was to develop an empirical method for predicting flow losses in flexible hose. Specific objectives for the contractor were set forth in the contract as follows:

1. Determine an empirical method for predicting flow losses in flexible hose while using a gas and a liquid as the test mediums and considering:
 - a. The effect of straight sections and bending
 - b. Hose characteristics such as types of material and convolutions, convolutions/unit length, convolution height, diameter, bend angle, bend radius, bend radius to diameter ratio, effective roughness factor, effective roughness to diameter ratio, Reynolds number and friction factor.
2. Obtain an adequate quantity of data so correlation of results may be achieved in a reliable and comprehensive manner.

Further, it was stated that all tests were to be performed under standard conditions utilizing air and water as the two (2) test mediums. The hose to be tested included:

1. Annular - both open and closed pitch convolutions were to be used.
2. Helical

Other criteria were:

1. Flexible hose diameters shall range from 1/2" to 3" inclusive.
2. Reynolds numbers shall range from 10^3 to maximum attainable.
3. Bend angles (Θ) shall vary from 0° to 180° inclusive with tests being performed at a sufficient number of standard intermediate angles so as to comply with Objective 2.
4. All test data used shall consist of the mean of at least three (3) runs per test set-up.
5. All other criteria shall be subject to Manned Spacecraft Center (MSC) approval.

Relation to Other NASA Efforts:

To the author's knowledge there have been two (2) similar projects supported by NASA.

1. A 2-year study of flow losses in flexible hose with air as the working medium was conducted by Mississippi State University in 1964-1966. The study considered only straight hose and was primarily aimed at a close investigation of the "critical" Reynolds number. Correlations were obtained for the air data produced at M. S. U. An explanation of the transition phenomena was not provided in this study.
2. A literature survey concerning losses in flexible hose was made for NASA by the Brown Engineering Co., Huntsville, Alabama. The results of this study were not available to this project.

Method of Approach and Principle Assumptions:

Definition of Friction Factor. Consider the steady flow of a fluid in a conduit of uniform cross section. The fluid will exert a force F on the solid surface of the conduit. This force may be split into two parts: F_s , that force which would be exerted by the fluid even if it were stationary, and F_k , that additional force associated with the kinetic behavior of the fluid.

The magnitude of the force F_k may be arbitrarily expressed as the product of a characteristic area A , a characteristic kinetic energy per unit

volume K , and a dimensionless quantity f , known as the friction factor:

$$F_k = AKf$$

Note that f is not defined until A and K are specified. With this definition f can usually be given as a relatively simple function of the Reynolds number and the system shape.

In this study A is taken to be πDL , where D is the minimum inside diameter of the flexible hose, and K is taken to be the quantity $1/2 \rho v^2$. Specifically, f is defined as

$$F_k = (\pi DL) \left(\frac{1}{2gc} \rho v^2 \right) f$$

The quantity f defined in this manner is sometimes called the Fanning friction factor.

Momentum Balance. According to Newton's second law, the rate of change of momentum equals the net applied force:

$$\frac{d(mv)}{dt} = \Sigma F$$

The surface forces acting on an element of fluid in a pipe are due to the upstream pressure, the downstream pressure, and the peripheral shear. The momentum equation for a differential element of fluid is then

$$P \frac{\pi D^2}{4} - (P + dP) \frac{\pi D^2}{4} - \tau_o \pi D dx = v \frac{\pi D^2}{4} \rho dv$$

The peripheral shear stress can be expressed in terms of the friction factor f . From the definition of the friction factor

$$\frac{F_k}{A} = \tau_o = Kf = \frac{\rho v^2}{2gc} f$$

Inserting this relationship in the momentum equation and simplifying gives

$$\frac{dP}{\rho} + v dv + \frac{4fv^2 dx}{D2gc} = 0$$

This equation can then be integrated so as to give the working equation for the evaluation of the friction factor.

Friction Factor for the Water System. For the flow of an incompressible fluid in a pipe of uniform cross section the integration of the momentum equation is straightforward.

$$dv = 0$$

$$\rho = \text{constant}$$

$$\therefore \frac{-\Delta P}{\rho} = 4f \frac{L}{D} \frac{v^2}{2g_c}$$

From this equation it follows that

$$f = \frac{1}{4} \left(\frac{D}{L} \right) \left(\frac{-\Delta P g_c}{\frac{1}{2} \rho v^2} \right)$$

This equation shows explicitly how f is calculated from experimental data.

Friction Factor for the Air System. In order to integrate the momentum equation for a compressible fluid the variable density and velocity has to be expressed in terms of the variable pressure. It will be assumed that the system is operating under approximately isothermal conditions.'

If all conditions are known at some upstream section, those at any arbitrary section downstream can be expressed in terms of known values at the upstream section. From the ideal gas equation of state,

$$\frac{P}{\rho} = \frac{P_1}{\rho_1} = RT = \text{constant}$$

From the equation of continuity,

$$v\rho = v_1\rho_1 = \text{constant}$$

$$\therefore \frac{dv}{v} = \frac{-dP}{P}$$

Inserting these relationships into the momentum equation and integrating gives:

$$\rho_1^2 - \rho_2^2 = \rho_1 v_1^2 P_1 \left(4f \frac{L}{D} - 2 \ln \frac{P_2}{P_1} \right)$$

Introducing the Mach number $M = v/c$, the final working equation becomes

$$4 \frac{fL}{D} = \frac{1}{kM_1^2} \left[1 - \left(\frac{P_2}{P_1} \right)^2 \right] - 2 \ln \frac{P_1}{P_2}$$

$$f = \frac{1}{4} \left(\frac{D}{L} \right) \left(\frac{1}{kM_1^2} \left[1 - \left(\frac{P_2}{P_1} \right)^2 \right] - 2 \ln \frac{P_1}{P_2} \right)$$

Variation of the Friction Factor. The friction factor depends on a number of variables:

1. The geometry of the pipe
2. Reynolds number
3. The ratio L/D

Along the length of the pipe it is assumed that the geometry follows a regular pattern, therefore, this variable should cause no variation in the friction factor along the length of the pipe.

If the velocity profile is fully established at the entrance to the test section, the friction factor will not depend on the ratio L/D . Only if the velocity profile is not fully established will this variable have to be considered.

This leaves only the investigation of the Reynolds number. Does the Reynolds number vary along the length of the pipe? For some cases it does, but for the great majority of cases it does not. Consider the case of an incompressible fluid flowing in a pipe of uniform cross section. Unless the fluid is heated, the density, viscosity, and diameter remain constant. The equation of continuity shows that the velocity also must remain constant, therefore, the Reynolds number must remain constant. It is obvious that the friction factor must remain constant along the length of the pipe.

For isothermal flow of compressible fluids the Reynolds number does not vary. If there are moderate changes in temperature the Reynolds number will not vary appreciably because the kinematic viscosity is not a strong function

of temperature. For large changes in temperature the variation of friction factor along the length of the pipe should be taken into account in the analysis.

Basic Data Generated and Significant Results:

1. Data Generated - Experimental measurements of flow rate, pressure drop, and temperature were carried out over a range of conditions. For the water experiment the ranges recorded were:

flow rate - <1 gpm to 300 gpm

Reynolds number - 6000-380,000

ΔP across test section - 3.5 psi/ft. to 0.01 psi/ft.

Temperature - 40°F → 80°F

For the air system:

Inlet pressure - 20 → 50 psig

Pressure drop ratio ($\frac{\Delta P}{P}$) 10^{-3} → 0.5

Temperature 50°F → 120°F

Reynolds number 10^4 → $5.5(10)^5$

SCFM 5 → 1100

The temperatures for the water system varied with the season, whereas for the air system, a combination of season and compressor effects caused the temperature to change.

2. Significant Results - The objectives of the research were accomplished in that: (1) the geometric parameters of the hose were investigated over the proposed flow rate ranges for the air and water systems, and (2) correlations relating friction factor and Reynolds number derived which gave satisfactory agreement between the values it predicts and those measured. For the water and air system the final equation is of the form:

$$f = \alpha Re^{\beta}$$

where α is a constant for any one hose. It can be calculated as a function of hose geometry. β is a second constant, the value of

which also depends on the hose geometry. The correlations for α and β are:

- a. Water system (annular hose)

$$\alpha = 0.01588 \left(\frac{\lambda - \sigma}{\epsilon} \right) - 0.00215$$

- b. Water system (helical hose)

$$\alpha = 0.02916 \left(\frac{\lambda - \sigma}{\epsilon} \right) - 0.00886$$

- c. Air system (annular hose)

$$\alpha = 0.02202 \left(\frac{\lambda - \sigma}{\epsilon} \right) - 0.00287$$

- d. Air system (helical hose)

$$\alpha = 0.04306 \left(\frac{\lambda - \sigma}{\epsilon} \right) - 0.01318$$

- e. Air and water systems (annular and helical)

$$\beta = 0.2987 \left(\frac{\sigma \epsilon}{\lambda^2} \right) - 0.0313$$

In all of the above equations λ is the pitch of convolution, σ represents a nominal width of convolution, and ϵ represents the depth of convolution.

Limitations:

Water System. The correlations presented were developed from data which extended over a Reynolds number range of from 6,000 to 380,000. The reliability of the correlations for Reynolds numbers below 6,000 is doubtful. However, it appears reasonable to use these correlations at Reynolds numbers moderately above 380,000. Below 6,000 the problem of transition from turbulent to laminar flow becomes critical - especially at large values of curvature.

The bend angle correlation was developed from data covering a range of D/R_B from 0 to 0.0787. This corresponds to a variation in the bend radius of from 3.18 ft. to infinity (straight hose). The correlation obtained for bend

angles was:

$$\frac{f}{f_0} = 1.0 + 7.898 \left(\frac{D}{R_B} \right)^{0.896}$$

Air System. The correlations were developed from data which extended over a Reynolds number range from 14,000 to 580,000. The reliability of the correlations for low Reynolds numbers are questionable due to the over-all scarcity of data in these ranges. The scatter over the entire range of Reynolds numbers is primarily due to the instrumentation used and the problem which was to be solved. The two were not compatible and it is felt that a new and sophisticated approach to the instrumentation problem is needed.

The correlations are also inadequate for a main stream velocity range above approximately 140 ft./sec. The Reynolds number at which this velocity occurs is a variable depending on the diameter of hose.

Although there is a question of validity at the low Reynolds numbers, it appears reasonable to accept the correlations in estimating design criteria.

Bend angle correlations were the same as those developed for the water system.

Implications of the Research:

The data compiled and the correlations derived therefrom show that the friction factor for flexible hose increases with an increase in the flow rate and the corresponding Reynolds number. The contrast with smooth pipes (in which the friction factor decreases with increasing Reynolds numbers) suggests that this results from additional friction sources not present in smooth pipes - for example, from eddy motion induced in the cavities inherent in the corrugated hose. The magnitude of these eddies and their influence on the flow pattern in the main stream apparently are functions of the flow rate. This concept also helps explain the relative magnitude of the friction factors in smooth and corrugated pipe for the same Reynolds number.

The behavior of the air data at high flow rates in the smaller hose is unique in that pressure appears to be a significant variable; for each inlet

pressure studied there was a Reynolds number at which the friction factors began to increase abruptly and deviated extensively from the established correlation. Preliminary calculations indicate that for any one pipe, this occurs at approximately the same linear velocity for all pressures (around 140 ft./sec. in the hose itself). This can be interpreted as being the velocity at which the shear or drag force exerted by the main flow on the fluid in the corrugation cavity becomes significant, causing a change in the nature or magnitude of the turbulence induced in the latter.

Recommendations for Further Studies:

The foregoing implications and others noted throughout the report on the work done to date emphasize the need for studies designed to develop a better understanding of the flow mechanisms. Successful investigation of the underlying theory would provide a sounder basis on which the empirical correlations can be improved, extended and/or interpreted.

This study should be concerned with such matters as the velocity distribution in the main stream and in the eddies induced in the corrugation cavities. Measurement of the point velocities for a range of flow rates in each of several different types and sizes of hose is strongly recommended as being the most valuable information of this sort that could be obtained.